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BUREAU OF STANDARDS
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ABSTRACT

In this report is given a discussion of time-temperature cooling curves at the center of steel samples of various sizes and shapes quenched into ordinary coolants, such as water, a commercial quenching oil, and air. Based on the described experiments a method is outlined by which cooling curves for various sizes and shapes quenched from various temperatures can be derived, provided the curve for one size from one quenching temperature is available and one constant is known for the coolant. Typical examples are given.

CONTENTS



## I. INTRODUCTION

In a recent report on mass effects in quenching [1] certain definite relations were developed by the authors between the size and shape of steel quenched and the center cooling velocity taken at 720° C. For rounds, spheres, and plates this cooling velocity was proportional to the surface per unit of volume raised to some power greater than 1 and less than 2. If $V$ represents the center cooling velocity, taken at 720°C., $S$ is the surface area, $W$ is the volume, $n$ and $C_2$ are constants depending upon the coolant, etc., these relations may be represented by the equation

$$V=\left(\frac{S}{W}\right)^n C_2 \qquad (1)$$

It was also demonstrated that the cooling time for certain intervals for small samples was inversely proportional to the designated cooling velocity. Thus, if $T$ is the cooling time for a given tempera-

[1] B. S. Tech. Paper No. 295.

ture change, $C$ and $C_1$ are constants, the relations referred to may be represented by the equation

$$T = \frac{CC_1}{V} \tag{2}$$

It may naturally be inferred from equations (1) and (2) that some very general relations exist between cooling times at the center of various sizes of the simple shapes (rounds, spheres, and plates), but in the report already referred to attention was largely directed to the cooling velocity taken at 720° C., as this had previously been shown [2] to be the best single factor from time-temperature cooling curves to represent the hardening produced in small or moderate size sections of carbon steels. While such cooling velocity relations are of general interest from several viewpoints, frequently questions arise regarding the cooling at lower temperatures and comparisons are desired of the greater part of the cooling range from the quenching to the final temperatures.

For example, the center temperatures may be desired in the forging of large masses, or the exact time required at which steel samples may be removed to avoid cracking without danger of reducing the center hardness, or otherwise modifying those properties which are dependent upon the manner of cooling through the hardening transformations.

Such cooling curves are also useful in comparisons of various coolants and particularly in determining what sizes of the simple shapes may be fully hardened to the center when made from steels for which the critical cooling velocities are known. Again they will show, at least in a general way, the range in sizes of the simple shapes which may be quenched to advantage in special coolants.

Aside from this, however, center cooling curves form the basis of comparison for a study of cooling at the surface and other portions of steel samples of various sizes and shapes, a subject which it is hoped may be considered at a later date.

It is the purpose of this report to summarize experiments already reported, together with results of additional tests in such a way that it will be possible to construct, by simple calculations, practically the entire time-temperature cooling curves (from the quenching temperature to about 200 to 250° C.) for the center of various sizes of the simple shapes when quenched from any temperature at or above 720° C. into typical coolants, such as water, an oil, and air. In the discussion of data the similarities and salient features of the quenching curves will, of course, be developed and will facilitate making similar compilations for other of the many coolants now used industrially or for experimental work.

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[2] H. J. French and O. Z. Klopsch, "Quenching diagrams for carbon steels in relation to some quenching media for heat treatment," Trans. A. S. S. T., 6, p. 251; September, 1924.

## II. MATERIALS AND TEST METHODS USED

As in previous cases, carbon or carbon-chromium steel samples of different sizes and shapes were quenched from various temperatures into motionless water, a commercial quenching oil (called No. 2 oil), or air, each at 18 to 23° C. A description of equipment and methods of procedure employed has already been given.[3]

It should be pointed out that in both the previous report and the tests now to be discussed, thermal effects of transformation were disregarded. Smooth curves were drawn from points above the transformations to points below and therefore cooling at intermediate temperatures in the neighborhood of 500 to 650° C. was approximated. Despite objections which may be raised to such procedure, it seems preferable to the use of a transformation-free metal. The thermal properties of all such metals as have been used or suggested for this purpose are quite different from those of ordinary steels, at least in some portions of the cooling range, and will not yield results closely approaching those obtained with the ordinary steels to which such treatments as are here considered are ordinarily applied and of most importance.

## III. EXPERIMENTAL RESULTS

### 1. COOLING FROM A FIXED TEMPERATURE

If in equation (2) there is substituted the value of $V$ given by equation (1) the following is obtained:

$$T=\frac{CC_1}{C_2}\left(\frac{W}{S}\right)^n \tag{3}$$

Since $C$, $C_1$, and $C_2$ are constants the product of $C$ and $C_1$ divided by $C_2$ will also be a constant. Equation (3) may then be rewritten as follows:

$$T=C_3\left(\frac{W}{S}\right)^n \tag{4}$$

This shows that the cooling time for a given temperature change at the center of small sizes of the simple shapes is proportional to the reciprocal of the surface per unit of volume raised to some power "$n$." The numerical values of this exponent have already been determined for a number of coolants and found to vary between 1 and 2; methods for determining the value of "$n$" for other coolants have also been outlined. To apply equation (4) it is then only necessary to evaluate the constant $C_3$ and determine upon what variables in quenching it is dependent in addition to the cooling range considered.

[3] See footnotes 1 and 2, pp. 365 and 366.

With the evaluation of the constant $C_3$ it should be possible to construct the complete time-temperature cooling curve for various sizes and shapes.

### 2. RELATION OF COOLING TIMES TO STEELS AND SHAPES QUENCHED

In the experimental work to be described all small samples were made of either high-carbon or high carbon-chromium steels, whereas the largest sections were prepared from commercial low-carbon steels. These variations in the composition of the steel are undesirable especially from the standpoint of the cooling at the lowest temperatures, for as shown at the right side of Figure 1 they introduce variations in the

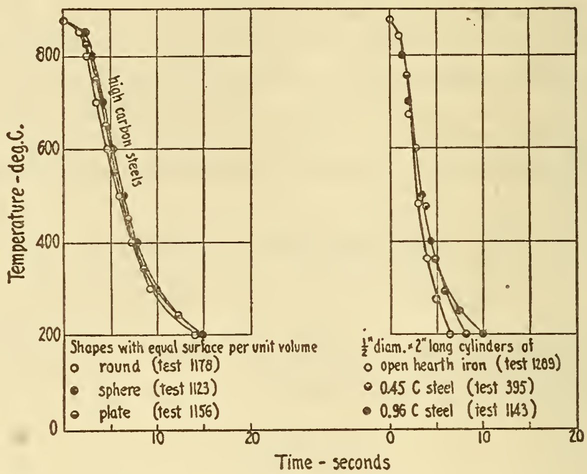


FIG. 1.—*Effect of composition of steel and shape of sample on time-temperature cooling curves taken at the center of small masses*

cooling times. With low carbon the cooling is more rapid in the range below about 500° C., but at higher temperatures such changes in composition produce changes in the cooling which are small and not easy to measure by the methods used in this investigation. It should, therefore, be kept in mind that the numerical values for certain constants later developed will give at the lower portions of the cooling range times slightly large for small sections of low-carbon steel and times which are somewhat low for large sections of high-carbon steels. As most previous work along similar lines with large sections has been with low-carbon steels the authors would have repeated with such steels many of the experiments already made with small sections of high-carbon steel were it not for the fact that the general relations and principles to be outlined are considered of greater importance than specific numerical values.

The authors have already shown that the cooling velocity in the neighborhood of 720° C. is a function of the surface per unit of volume and does not vary with the shape of sample. Likewise, it has been shown that the cooling time for certain intervals is inversely proportional to this cooling velocity. At the left side of Figure 1 it is shown that within limits of experimental error the entire cooling as well is independent of the shape of sample. While this has been checked only on small and moderate size sections, it is a reasonable assumption that the law as stated should be more nearly correct the larger the specimens. Further indirect evidence for the validity of this assumption will be found in data given in subsequent sections of this report.

### 3. DATA SHOWING THAT IN A GIVEN COOLANT THE CENTER OF A GIVEN STEEL SAMPLE COOLS IN EQUAL TIMES TO EQUAL PROPORTIONS OF THE COOLING RANGE

Before taking up in detail the general relations between cooling times and the size and shape of steel the effect of variation in quenching temperature on the manner of cooling will be considered. The times required to cool the center of spheres of different sizes from 730 (or 760), 815, 875, and 950° C. to various lower temperatures in water, a commercial quenching oil and air are summarized in Tables 1 and 2. If these times are plotted against temperature expressed as a proportion of the cooling range (quenching temperature to coolant temperature), curves similar to those in Figure 2 are obtained.[4] It will be observed that the center of the sample cools to equal proportions of the cooling range in equal times. It therefore follows that any relations developed for one initial temperature are immediately applicable to any other provided only that temperature is expressed as a proportion of the cooling range. However, this has only been shown to apply to quenching from above the transformations, at or above about 720° C.

[4] For coolants at atmospheric temperatures no appreciable error is introduced and calculations are simplified if temperatures are expressed as a proportion of the temperature of quench instead of as a proportion of the cooling range. This method was used in plotting Figures 2 and 6 and in deriving data in Tables 1 and 3 relating to coolants at ordinary temperatures. It will introduce greater errors for coolants at much higher temperatures.

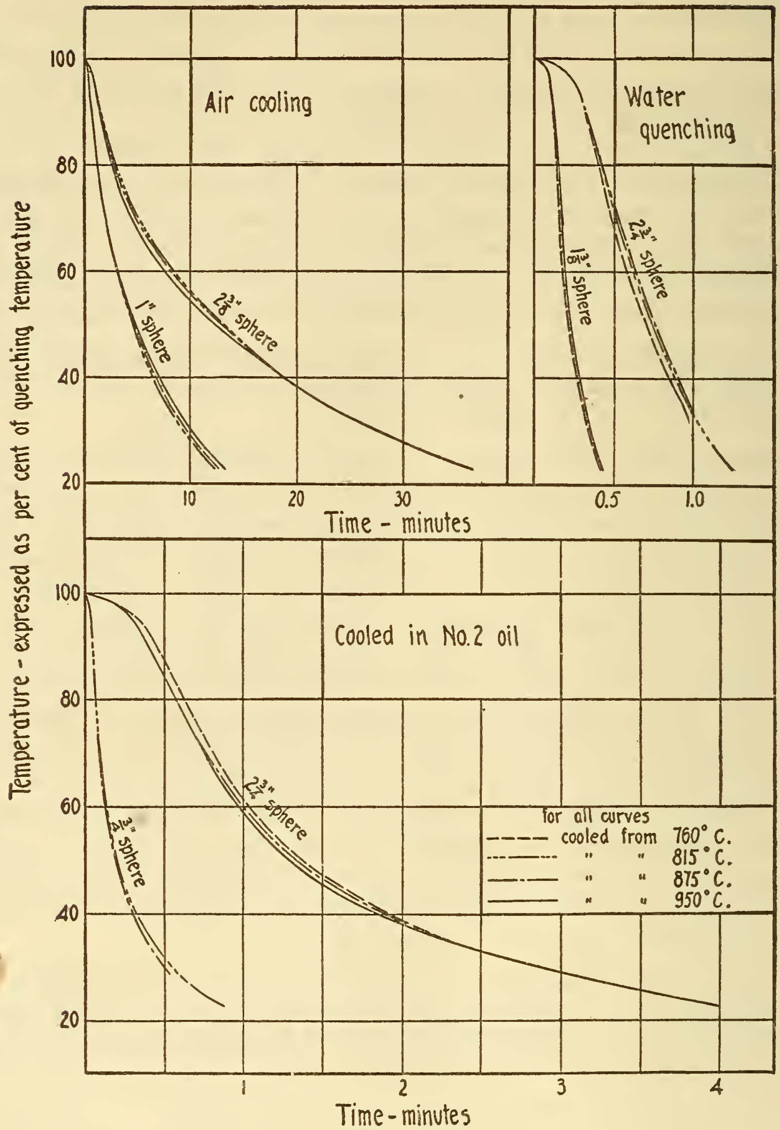


Fig. 2.—*Effect of quenching temperature on the center cooling curves of steel samples immersed in various coolants*

Note that all temperatures are expressed as a proportion of the initial (quenching) temperature. (Refer to footnote 4 of the text.)

TABLE 1.—*Effect of quenching temperature on the center cooling of steel specimens of various sizes and shapes in different media*

| Run number | Size in inches | Coolant | Quenching temperature | Time in minutes to cool to proportion of quenching temperature indicated [1] | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 97.2 per cent | 91.4 per cent | 80.0 per cent | 68.6 per cent | 57.2 per cent | 45.7 per cent | 34.3 per cent | 22.9 per cent |
| | | | ° C. | | | | | | | | |
| 1322 | 2¾ sphere | Water | 760 | 0.21 | 0.30 | 0.39 | 0.49 | 0.61 | 0.76 | 0.93 | ------- |
| 1324 | ½ by 2 round | do | 760 | .018 | .026 | .035 | .044 | .055 | .068 | .093 | ------- |
| 1325 | ½ by 2 round | do | 760 | .017 | .024 | .033 | .043 | .052 | .063 | .082 | ------- |
| 1333 | 2¾ sphere | No. 2 oil | 760 | .28 | .43 | .63 | .84 | 1.13 | 1.62 | ------- | ------- |
| 1331 | ½ by 2 round | do | 730 | .025 | .038 | .064 | .095 | .145 | .255 | .487 | ------- |
| 1495 | 1 sphere | Air | 760 | .18 | .53 | 1.30 | 2.25 | 3.31 | 5.60 | 8.30 | 13.0 |
| 1496 | 1⅜ sphere | do | 760 | .25 | .75 | 1.85 | 3.33 | 5.42 | 6.47 | 12.22 | 18.50 |
| 1509 | 1 sphere | Water | 815 | .029 | .048 | .068 | .089 | .111 | .139 | .188 | .270 |
| 1510 | 1⅞ sphere | do | 815 | .088 | .139 | .192 | .256 | .323 | .402 | .520 | .780 |
| 1511 | 2¾ sphere | do | 815 | .203 | .292 | .413 | .542 | .673 | .817 | .992 | 1.25 |
| 1489 | ¾ sphere | No. 2 oil | 815 | .033 | .050 | .077 | .111 | .163 | .258 | .427 | .883 |
| 1491 | 1⅜ sphere | do | 815 | .087 | .125 | .192 | .278 | .422 | .622 | 1.07 | ------- |
| 1492 | 1⅞ sphere | do | 815 | .15 | .205 | .300 | .437 | .637 | .933 | 1.52 | ------- |
| 1493 | 2⅜ sphere | do | 815 | .20 | .28 | .46 | .66 | .903 | 1.27 | 2.12 | ------- |
| 1488 | ¾ sphere | Air | 815 | .133 | .327 | .783 | 1.53 | 2.6 | 4.0 | 5.93 | 9.5 |
| 1487 | 1 sphere | do | 815 | .183 | .408 | 1.07 | 2.10 | 3.58 | 5.43 | 8.08 | 12.42 |
| 1486 | 1⅜ sphere | do | 815 | .30 | .667 | 1.63 | 3.15 | 5.38 | 8.33 | 12.2 | 18.33 |
| 1485 | 1⅞ sphere | do | 815 | .39 | .92 | 2.33 | 4.55 | 7.80 | 12.25 | 18.2 | 28.00 |
| 1484 | 2⅜ sphere | do | 815 | .52 | 1.17 | 2.97 | 5.67 | 9.75 | 15.50 | 26.67 | 36.67 |
| 1483 | 2¾ sphere | do | 815 | .72 | 1.52 | 3.71 | 7.32 | 12.67 | 20.37 | 30.00 | 48.00 |
| 1513 | 1⅜ sphere | Water | 950 | .080 | .110 | .150 | .183 | .219 | .263 | .325 | .423 |
| 1514 | 2⅜ sphere | do | 950 | .146 | .223 | .313 | .403 | .500 | .620 | .771 | 1.029 |
| 1507 | 2⅜ sphere | No. 2 oil | 950 | .187 | .300 | .445 | .607 | .817 | 1.17 | 1.83 | 3.37 |
| 1508 | 2¾ sphere | do | 950 | .233 | .383 | .670 | .767 | 1.03 | 1.45 | 2.33 | 4.00 |
| 1497 | ¾ sphere | Air | 950 | .117 | .270 | .667 | 1.22 | 2.17 | 3.57 | 5.40 | 8.50 |
| 1498 | 1 sphere | do | 950 | .183 | .453 | 1.11 | 2.03 | 3.63 | 5.95 | 8.92 | 13.63 |
| 1499 | 1⅜ sphere | do | 950 | .267 | .667 | 1.58 | 2.97 | 5.27 | 8.75 | 13.58 | 21.00 |
| 1501 | 2⅜ sphere | do | 950 | .482 | 1.000 | 2.50 | 4.78 | 6.65 | 14.87 | 23.33 | 36.50 |
| 1502 | 2¾ sphere | do | 950 | .617 | 1.28 | 3.03 | 5.88 | 10.67 | 18.37 | 29.00 | 45.17 |

[1] For example, the range from 1,000 to 600° C. when quenching from 1,000° C. is given as 60 per cent. (Refer to footnote 4 of the text.)

TABLE 2.—*Effect of size and shape on the center cooling when steels are cooled in various media*

| Run number | Size in inches | Cooled in | S/W | Time in minutes to cool from 875° C. to— | | | | | | | | | "X" minutes |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 850° C. | 800° C. | 700° C. | 600° C. | 500° C. | 400° C. | 300° C. | 250° C. | 200° C. | |
| Spheres: | | | | | | | | | | | | | |
| 1229 | ¾ | Water | 8 | 0.021 | 0.028 | 0.039 | 0.05 | 0.063 | 0.081 | 0.108 | | | 0.018 |
| 1124 | 1⅜ | do | 4.46 | .07 | .092 | .124 | .155 | .19 | .233 | .292 | 0.337 | 0.415 | .065 |
| 1125 | 1⅝ | do | 3.7 | .087 | .118 | .165 | .208 | .258 | .318 | .403 | .466 | | .079 |
| 1126 | 1⅞ | do | 3.2 | .103 | .147 | .207 | .264 | .33 | .409 | .522 | .600 | .74 | .090 |
| 1127 | 2⅜ | do | 2.58 | .163 | .223 | .312 | .406 | .512 | .631 | .788 | .903 | | .147 |
| 1128 | 2¾ | do | 2.1 | .233 | .305 | .426 | .558 | .71 | .87 | 1.07 | | | .22 |
| 1544 | 4¾ | do | 1.26 | .60 | .87 | 1.23 | 1.57 | 1.85 | 2.15 | 2.5 | 2.70 | 2.97 | .55 |
| Rounds: | | | | | | | | | | | | | |
| 1143 | ½ by 2 | do | 9 | .015 | .022 | .033 | .045 | .058 | .075 | .100 | | | .013 |
| 1176 | 1¼ by 5 | do | 3.6 | .095 | .14 | .192 | .242 | .293 | .348 | .413 | .460 | | .083 |
| 393 | 1½ by 4½ | do | 3.11 | .117 | .170 | .243 | .300 | .357 | .425 | .510 | .563 | .640 | .093 |
| 1170 | 1½ by 6 | do | 3.00 | .12 | .157 | .217 | .273 | .337 | .400 | .483 | .54 | .627 | .108 |
| 394 | 2 by 6 | do | 2.34 | .19 | .27 | .39 | .48 | .58 | .68 | .82 | .90 | .98 | .167 |
| Plates: | | | | | | | | | | | | | |
| 1081 | ⅜ by ⅜ by 1½ | do | 8 | .014 | .023 | .040 | .056 | .071 | .087 | .106 | .115 | .127 | .0125 |
| 1088 | ⅜ by ⅜ by 1½ | do | 8 | .018 | .029 | .046 | .063 | .078 | .095 | .114 | .127 | .142 | .016 |
| 1102 | ⅜ by ⅜ by 1½ | do | 8 | .015 | .025 | .042 | .057 | .071 | .087 | .106 | .117 | .129 | .0125 |
| 1082 | ½ by 2 by 2 | do | 6 | .024 | .039 | .063 | .084 | .107 | .132 | .163 | .180 | .200 | .021 |
| 1103 | ½ by 2 by 2 | do | 6 | .025 | .038 | .062 | .085 | .110 | .137 | .168 | .187 | .205 | .0233 |
| 1152 | ½ by 2 by 2 | do | 6 | .028 | .048 | .075 | .099 | .125 | .155 | .193 | .222 | | .025 |
| 1083 | 9/16 by 2¼ by 2¼ | do | 5.33 | .027 | .047 | .080 | .112 | .140 | .170 | .202 | .220 | .243 | .0233 |
| 1154 | 9/16 by 2¼ by 2¼ | do | 5.33 | .040 | .061 | .084 | .108 | .133 | .163 | .210 | .243 | | .031 |
| 1104 | 11/16 by 2¾ by 2¾ | do | 4.36 | .038 | .065 | .105 | .142 | .175 | .213 | .267 | .280 | .305 | .034 |
| 1133 | 11/16 by 2¾ by 2¾ | do | 4.36 | .040 | .067 | .107 | .142 | .174 | .205 | .238 | | | .035 |
| 1100 | 0.945 by 4 by 4 | do | 3.12 | .100 | .152 | .213 | .262 | .313 | .365 | .418 | | | .088 |
| Spheres: | | | | | | | | | | | | | |
| 1217 | ¾ | No. 2 Oil | 8 | .032 | .050 | .078 | .107 | .150 | .233 | .388 | .516 | | .028 |
| 1215 | 1 | do | 6 | .050 | .079 | .117 | .160 | .225 | .372 | .675 | .908 | | .043 |
| 1265 | 1 | do | 6 | .050 | .075 | .110 | .148 | .220 | .337 | .646 | | | .043 |
| 1221 | 1⅜ | do | 4.46 | .087 | .135 | .213 | .303 | .428 | .606 | .927 | | | .08 |
| 1222 | 1⅜ | do | 4.46 | .088 | .128 | .193 | .268 | .379 | .583 | 1.00 | | | .08 |
| 1201 | 1⅞ | do | 3.2 | .13 | .23 | .38 | .57 | .85 | 1.27 | | | | .108 |
| 1207 | 1⅞ | do | 3.2 | .14 | .21 | .31 | .43 | .60 | .98 | | | | .133 |
| 1211 | 1⅞ | do | 3.2 | .15 | .22 | .33 | .45 | .63 | 1.08 | 1.65 | 2.12 | | .135 |
| 1212 | 2¾ | do | 2.1 | .25 | .37 | .54 | .78 | 1.08 | 1.57 | 2.28 | | | .217 |
| 1543 | 4¾ | do | 1.26 | .73 | 1.10 | 1.60 | 2.10 | 2.70 | 3.7 | 5.8 | 7.5 | 9.85 | .67 |
| 1536 | 11¼ | do | .533 | 3.55 | 5.12 | 7.10 | 8.75 | | | | | | 3.2 |
| Rounds: | | | | | | | | | | | | | |
| 1240 | ¾ by 3 | do | 6 | .05 | .083 | | | | | | | | .043 |
| 1263 | ¾ by 3 | do | 6 | .038 | .068 | .12 | .15 | .263 | .403 | .657 | | | .037 |
| 1257 | 1 by 4 | do | 4.5 | .053 | .088 | .160 | .237 | .323 | .470 | .82 | | | .047 |
| 1244 | 1¼ by 5 | do | 3.6 | .113 | .172 | .26 | .35 | .48 | .73 | | | | .102 |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Spheres: | | | | | | | | | | | | | |
| 1468 | 2⅜ | Air | 2.58 | .60 | 1.25 | 2.83 | 5.33 | 9.5 | 15.5 | 23.5 | 29.0 | 36.8 | .55 |
| 1541 | 4¾ | do | 1.26 | 1.50 | 2.83 | 5.83 | 11.0 | 20.0 | 31.0 | 46.83 | 60.0 | 76.67 | 1.25 |
| 1535 | 11¼ | do | .533 | 6.3 | 12.0 | 25.5 | 40.0 | 58.0 | 82.0 | 120.5 | 145.0 | 185.0 | 5.5 |
| Rounds: | | | | | | | | | | | | | |
| 388 | ½ by 2 | do | 9 | .10 | .30 | | | | | | | | .067 |
| 1239 | ½ by 2 | do | 9 | .083 | .242 | .633 | | | | | | | .05 |
| 1476 | ½ by 2 | do | 9 | .12 | .28 | .67 | 1.28 | 2.25 | 3.63 | 5.38 | 6.70 | 8.56 | .100 |
| 1540 | ½ by 2 | do | 9 | .11 | .35 | .91 | 1.57 | 2.33 | 3.47 | 5.2 | 6.46 | 8.17 | .083 |
| 1241 | ¾ by 3 | do | 6 | .167 | .44 | 1.11 | | | | | | | .133 |
| 1248 | ¾ by 3 | do | 6 | .15 | .41 | 1.08 | | | | | | | .10 |
| 1243 | 1 by 4 | do | 4.5 | .21 | .55 | 1.45 | | | | | | | .15 |
| 1245 | 1¼ by 5 | do | 3.6 | .30 | .73 | 1.9 | | | | | | | .233 |
| 1247 | 1½ by 6 | do | 3.0 | .43 | .98 | 2.47 | | | | | | | .35 |
| 1250 | 2 by 8 | do | 2.25 | .70 | 1.40 | 3.25 | | | | | | | .60 |
| | | | | Time in minutes to cool from 882° C. to— | | | | | | | | | |
| | | | | 857° C. | 806° C. | 705° C. | 605° C. | 504° C. | 403° C. | 302° C. | 252° C. | 202° C. | |
| Cubes: | | | | | | | | | | | | | |
| Harper [1] | 12 | Water | .500 | 7.5 | 10.3 | 13.1 | 14.4 | 15.6 | 17.1 | 19.1 | 20.3 | 21.6 | 7.0 |
| Do | 12 | Air | .500 | 9.5 | 17.0 | 34.2 | 54.0 | 78.0 | 110.0 | 154.0 | 184.0 | 232.0 | 9.0 |
| | | | | Time in minutes to cool from 900° C. to— | | | | | | | | | |
| | | | | 874° C. | 822° C. | 720° C. | 617° C. | 515° C. | 411° C. | 309° C. | 257° C. | 206° C. | |
| Law [1] | 18 | Water | .333 | 13.7 | 17.2 | 22.0 | 25.5 | 28.3 | 31.8 | 36.2 | 38.7 | 42.3 | 13.0 |
| Do | 18 | "Oil" | .333 | 13.0 | 17.8 | 23.9 | 29.0 | 35.0 | 41.5 | 49.5 | 54.5 | 61.3 | 12.0 |
| Do | 18 | Air | .333 | 21.0 | 35.0 | 64.0 | 101.5 | 142.0 | 203.0 | 273.0 | | | 17.0 |
| | | | | Time in minutes to cool from 1,252° C. to— | | | | | | | | | |
| | | | | 1,217° C. | 1,144° C. | 1,001° C. | 859° C. | 716° C. | 572° C. | 429° C. | 358° C. | 287° C. | |
| Rounds: | | | | | | | | | | | | | |
| Bash [1] | 24 by 134 | do | .183 | 48.3 | 77.5 | 115.0 | 154.0 | 250.0 | 366.0 | 510.0 | | | 45.0 |

[1] Refer to footnotes 5, 6, and 7 of the text.

### 4. EVALUATION OF THE "TIME-CONSTANT"

In Table 2 are tabulated the times required for cooling from 875° C. to various lower temperatures. These numerical values were secured from a large number of cooling curves taken when quenching the specified sizes and shapes into water, No. 2 oil, and air. Included also are values taken from curves for large sections published by Law [5] and Bash; [6] Harper's data have not yet been published.[7] From these data the values of $C_3$ in equation (4) were calculated and it was found that its numerical value depended not only upon the coolant and the cooling interval, but also upon the surface per unit of volume. Under such conditions the direct evaluation of this constant for even one coolant involves a great deal of work, including such extensive experiments that when completed they make the evaluation unnecessary for there have been obtained experimentally all required data. For this reason the results of the calculations referred to are not here included.

Obviously what is needed is to evaluate $C_3$ in terms of readily determinable factors associated with the surface per unit of volume and the coolant so that with a cooling curve for the center of one size of the simple shapes immersed in a given coolant, curves can be derived by means of simple calculations for various sizes and shapes when quenched into the same coolant.

Without giving in detail the mechanism by which these relations were developed, one feature should be mentioned. With the exception of the first drop in temperature, say, for an interval of 20° C., the cooling curves for various sizes appeared to closely follow the relations represented by equation (4). More specifically, when deriving time-temperature cooling curves for the center of large sections from constants determined from experiments on small samples it was found that the derived curves were in most cases generally parallel to but offset at some distance from curves determined experimentally. The derived curves in practically all cases showed more rapid cooling than was observed directly by experiment, and the magnitude of this difference appeared to increase with the section, and hence with decrease in the surface per unit of volume.

Consider for a moment that heat is first taken away from the surface and an appreciable time elapses before there can be an appreciable drop in temperature at the center. In small sizes $\left(\text{high values of } \frac{S}{W}\right)$ where most rapid cooling is obtained this dif-

[5] E. F. Law, "Effect of mass on heat treatment," Jour. Iron and Steel Inst., 97, p. 333; 1918.

[6] F. E. Bash, "Forging temperature and rate of heating and cooling of large ingots," Trans. Am. Inst. of Min. and Met. Engrs., "pyrometry volume," p. 614; 1920.

[7] The cooling curves at the center of the 12-inch cube quenched in water and also cooled in air were taken from experiments recently carried out by J. F. Harper, Allis-Chalmers Manufacturing Co., Milwaukee, Wis.

ference will be very small, whereas in the relatively large sections $\left(\text{small values of } \frac{S}{W}\right)$ when the surface is far removed from the center, it will be large.

It is extremely difficult to determine the time required for the first very small temperature drop at the center. Therefore, this factor, which will hereafter be called "lag," will be defined for the purpose of this report as the time required to drop a number of degrees equal to 2 per cent of the cooling ranges (equals 17.1° C. for a quenching temperature of 875° C. when the coolant is at 20° C.). Actually the "lag" increases with decrease in the surface per unit of volume, and hence with increase in size of any one of the simple shapes. (See fig. 3.)

Based on reasoning along this line and a study of the experimental data summarized in the various tables and charts in this report the following emperical relation was developed:

$$T-x=y\left(\frac{W}{S}\right)^n \tag{5}$$

in which

$T$ is the cooling time from the quenching temperature to any lower temperature (in this report expressed in minutes),

$x$ is the "lag" in minutes; represents the cooling time for an initial drop in temperature equal to 2 per cent of the cooling range,

$y$ is the "time constant."

$S$ is the surface area (in this report given in square inches),

$W$ is the volume (in this report given in cubic inches),

$n$ is the exponent depending only on the coolant; its numerical values are the same as in all previous equations in this and the preceding report on mass effects, already referred to in the text.

With this equation the time-temperature cooling curves for the center of various sizes of the simple shapes may be derived when the steel is quenched into any ordinary coolant provided only two pieces of information are available: (1) the exponent "$n$" must be known for the particular coolant under consideration; and (2) there must be available an accurate center cooling curve for some one size of the simple shapes when quenched from any temperature at or above about 720° C. into this coolant. In other words, if this exponent and one good cooling curve are available, curves can be derived for the whole ranges of sizes and shapes quenched from temperatures at or above 720° C.

Time-temperature cooling curves are not exceedingly difficult to obtain for even with so-called drastic coolants, good results may be

secured with ordinary pyrometer equipment and stop watches if the experiment is carried out with moderately large sections which keep down the center cooling velocities. The value of the exponent "$n$" can be determined, if not now known, by methods already described,[8] and when once obtained for a given coolant is fixed for the various sizes and shapes and independent of the quenching temperature. There then remain the "lag," $x$, and the "time-constant," $y$, for evaluation before the time, $T$, from the quenching temperature to any lower temperature can be directly determined from equation (5).

A study of the "lag," $x$, in cooling curves taken when quenching a wide variety of sizes and shapes into water, the oil and air shows that in any one coolant this increases with decrease in the surface per unit

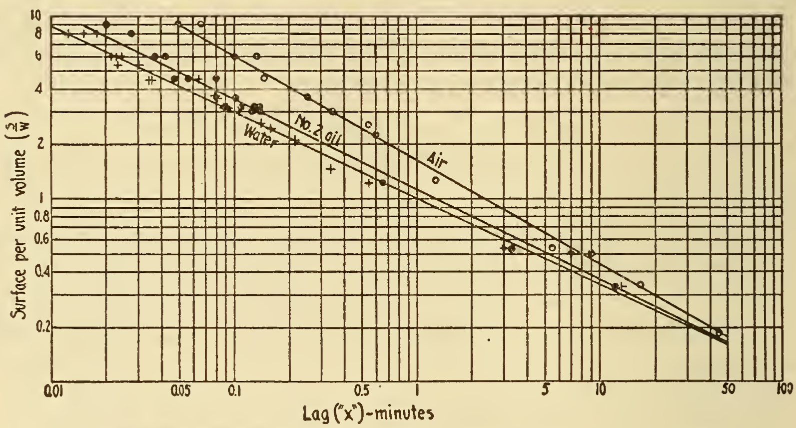


FIG. 3.—*Relation between "lag" in center cooling and the surface per unit of volume of steel samples immersed in water, oil, or air*

The method of determining "lag" is described in the text.

of volume. It is greater for a given surface per unit of volume when cooling in air than when quenching in oil and likewise greater in oil than in the more "drastic" water quench. As indicated in Figure 3 in which is shown the relation, plotted logarithmically, between "lag" and surface per unit of volume the differences between water, oil, and air diminish as the size of sample increases (as the surface per unit of volume decreases). This feature again confirms the view, already expressed, that the center cooling of large masses is affected to a much smaller degree by the coolant than small sections because the surface is far removed from the center and is small in comparison with the volume of metal to be cooled.

No attempt was made to express mathematically the relation between "lag," surface per unit of volume and the coolant, for it is a simple matter to prepare a chart covering these relations by which

[8] See footnote 1, p. 365.

values of the "lag" may be scaled directly. This "lag" chart, which should be more useful from a practical standpoint than equations, is reproduced in Figure 4, and for the sake of reducing its size semi-logarithmic coordinates were used.

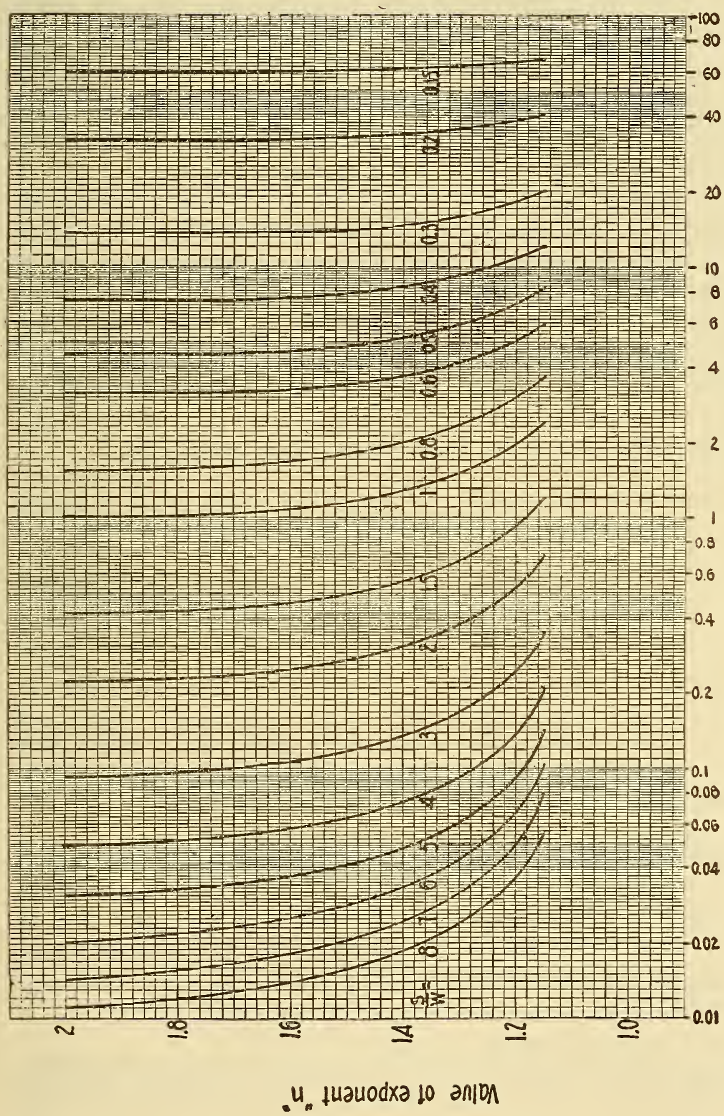


FIG. 4.—"*Lag*" *at the center of various sizes and shapes when quenched into various coolants*

From this chart the value of $x$ in equation (5) may be determined for various coolants and different sizes and shapes of steel. The value of the "lag," $x$, may be scaled directly in minutes if the exponent, $n$, in equation (5) is known for the coolant considered.

The "lag" for any size of the simple shapes may be found in ordinary coolants by locating the intersection of the line representing exponent "$n$" for the coolant with the curve for the surface per unit of volume equal to that of the sample in question. This chart is based on the lines drawn through the "scatter" of points for water, the oil,

and air in Figure 3. Each of the lines representing surface per unit of volume in Figure 4 are therefore based on three points, those, respectively, for water ($n=1.75$), the oil ($n=1.4$), and air ($n=1.15$). Their exact curvature may, therefore, not have been obtained, but undoubtedly they are drawn very close to proper form because with very slow cooling ($n=$approximately 1) the lag would be very large so that each of the curves must bend sharply in the direction shown. However, the principles involved in the preparation of this chart are considered of more importance than the numerical values which will change for different metals.

Since $x$ of equation (5) is now known for any ordinary coolant for which the value of the exponent "$n$" is available only the "time-constant" $y$ must be secured. The solution of equation (5) for $y$, based on experiments with a variety of sizes and shapes, was carried out and as shown in Figure 5, this is dependent only upon the cooling interval, provided the final temperature is expressed as a proportion of the initial (quenching) temperature. Average values for $y$ are given in Table 3. The direct application of equation (5) may now be considered as all terms except the time $T$ have been evaluated.

TABLE 3.—*Values of the time constant "y" for various cooling ranges in various coolants*

| Coolant | Time constant for cooling ranges beginning at the quenching temperature and ending at the temperature shown (expressed as per cent of quenching temperature) [1] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 97.2 per cent | 91.4 per cent | 80.0 per cent | 68.6 per cent | 57.2 per cent | 45.7 per cent | 34.3 per cent | 28.6 per cent | 22.9 per cent |
| Water | 0.18 | 0.51 | 1.02 | 1.48 | 1.98 | 2.53 | 3.27 | 3.68 | 4.40 |
| No. 2 oil | .17 | .44 | 1.04 | 1.53 | 2.54 | 3.97 | 6.63 | 9.05 | -------- |
| Air | .44 | 3.04 | 9.19 | 17.92 | 29.25 | 44.82 | 65.57 | 78.22 | 99.82 |

[1] For example, the range from 1,000 to 600° C., when quenching from 1,000° C., is given as 60 per cent. (See footnote 4 of the text.)

For example, consider motionless water at 20° C. for which the value of the exponent "$n$" is equal to 1.75. If a time-temperature cooling curve is available for a sample with a surface per unit of volume of 1 when quenched from, say, 875° C., the following procedure is used in the derivation of cooling curves for other sizes and shapes quenched from temperatures at or above about 720° C.

First determine from the known cooling curve the lag ($x$) and solve the equation (5) for the time constant $y$ for various cooling ranges, for example, from the quenching temperature of 875 to 800, from 875 to 700, from 875 to 600° C., etc. The values of $y$ obtained for each interval apply to the various sizes and shapes which may be considered.

Secondly, determine from the "lag" chart, Figure 4, the values of $x$ for the various sizes and shapes for which data are desired. These values are obtained from the intersection of the line $n=1.75$ with the respective surfaces per unit of volume of the sizes and shapes to be considered

Third, to locate the cooling curve, substitute in equation (5) the proper value of $x$ for the size considered, the proper value of surface per unit of volume, and the value of $y$ for each of the cooling intervals desired and solve in each case for the cooling time $T$.

If these values of $T$ are plotted against the final temperature expressed as a proportion of the cooling range a time-temperature cooling curve will be obtained which will represent the cooling of the particular size and shape considered when quenched from any temperature at or above about 720° C.

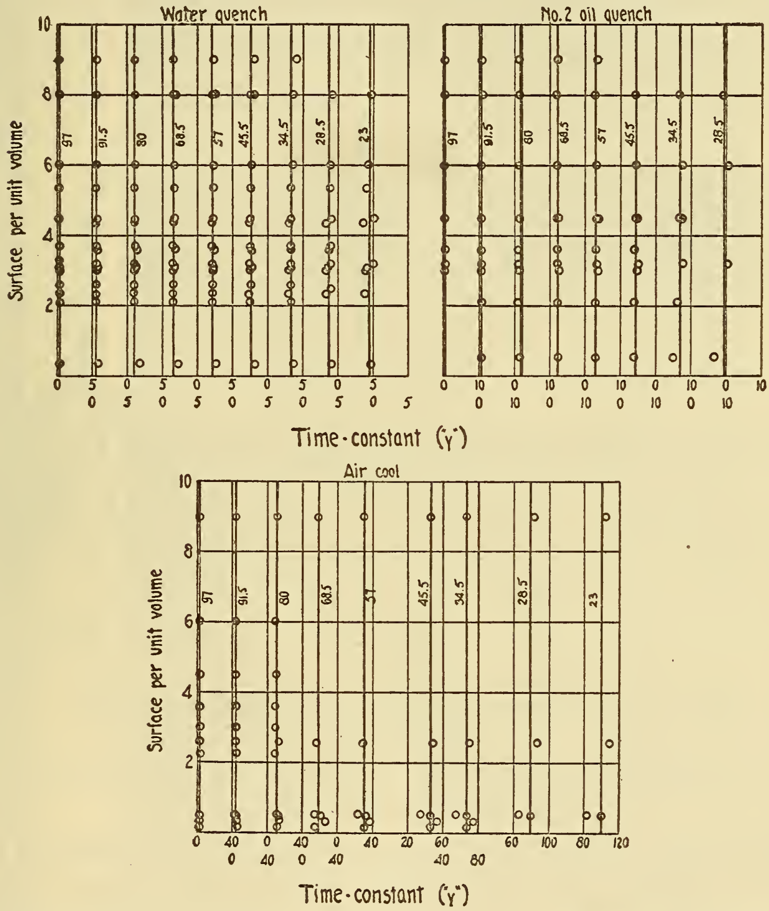


FIG. 5.—*Relation between the "time-constant," y, for various cooling ranges and the surface per unit of volume of the sample*

Numerical values on each vertical $y$-line represent the cooling range from the quenching temperature to a lower temperature expressed as a per cent of the temperature of quench. (Refer to footnote 4 of the text.)

If this process is repeated for various values of surface per unit of volume a series of cooling curves will be obtained for the various sizes and shapes quenched into this coolant

The results of computations carried out for air in a manner similar to that described above gave the typical results shown in Figure 6. This chart, which has been plotted to logarithmic coordinates to

reduce its size, is not presented so much to give numerical values as to demonstrate the method of preparation which may be applied to many coolants. It is to be understood that the term coolant here

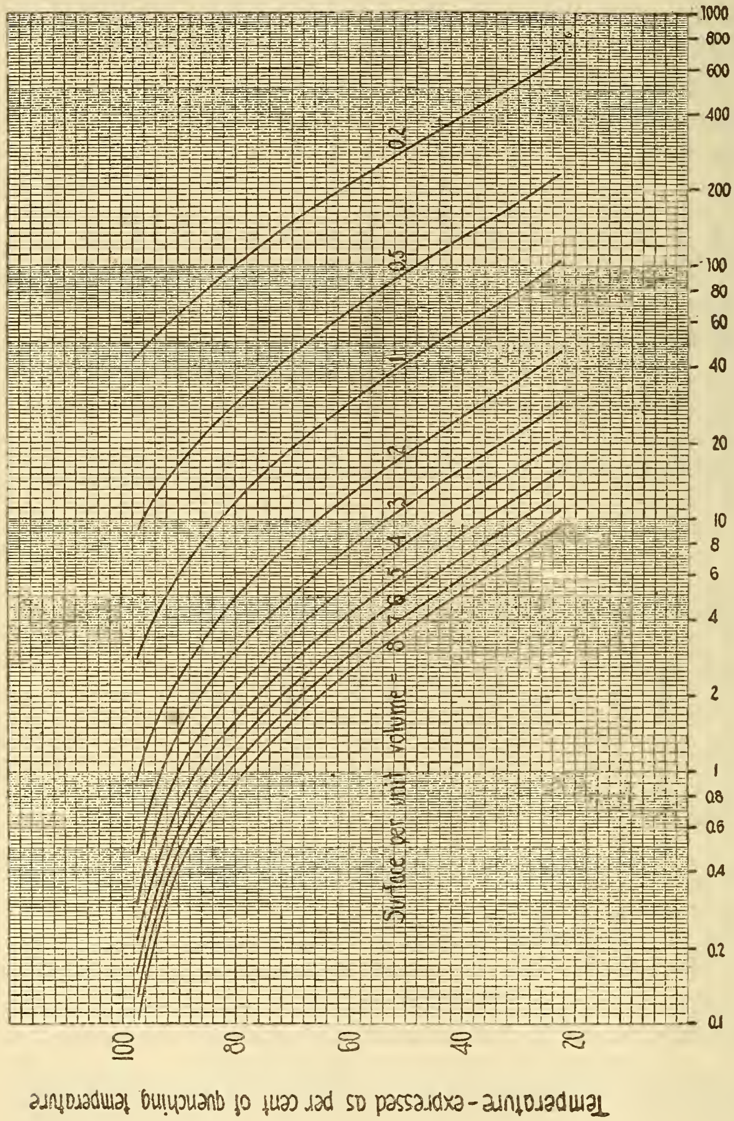


FIG. 6.—*Derived time-temperature cooling curves for the center of different sizes and shapes cooled in air*

Semilogarithmic coordinates were used to reduce the size of this chart. Note that the sizes and shapes are indicated by the values of surface per unit of volume and that all temperatures are expressed as a proportion of the quenching temperature. (Refer to footnote 4 of the text).

refers to a medium at a particular temperature with a particular rate of circulation or motion; a change in any one of these or other important factors represents a change in the coolant.

## IV. GENERAL DISCUSSION AND SUMMARY

Admittedly, the described methods and relations are empirical for they are not based on the fundamental constants of materials, but upon direct experimental determination of cooling times under a variety of conditions. Their accuracy or that of similar computations for other coolants depends upon the accuracy attained in the experiments upon which they are based. For this reason it would be unwise, under ordinary conditions, to base calculations for a given coolant on a single cooling curve. A safer course would be to secure curves for at least two widely different sizes and shapes and in both cases to demand at least two consistent experiments.

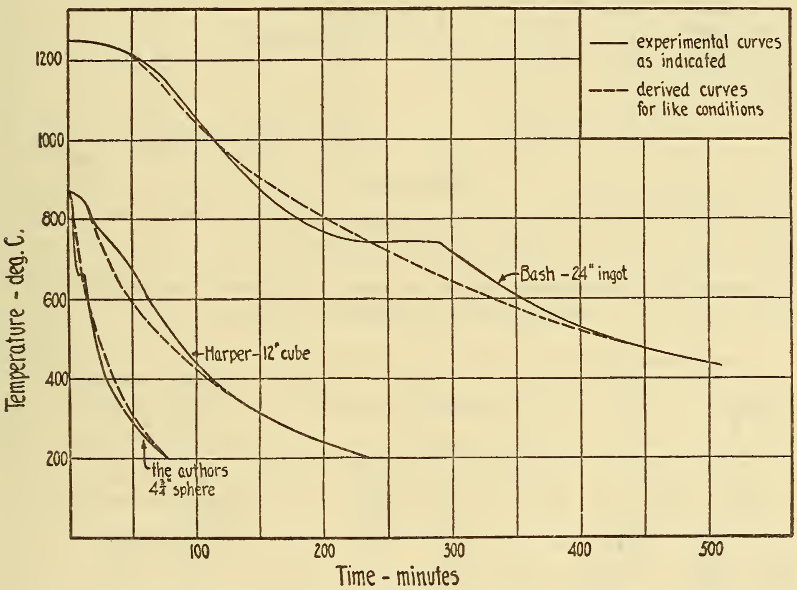


FIG. 7.—*Comparisons of derived and experimental air-cooling curves for the center of various sizes and shapes*

However, with accurate basic data from which to make calculations, cooling curves will be obtained which are close to those determined experimentally and more representative of the actual cooling than curves derived at this time from purely theoretical considerations because the latter include assumptions and approximations of the values of certain physical constants of materials which are not now accurately known. This has been fairly well established.

Comparisons of derived curves with those determined experimentally for different sizes and shapes quenched in water, oil, or cooled in air are given in Figures 7, 8, and 9. As far as was practicable these comparisons were made with results of other investigators and

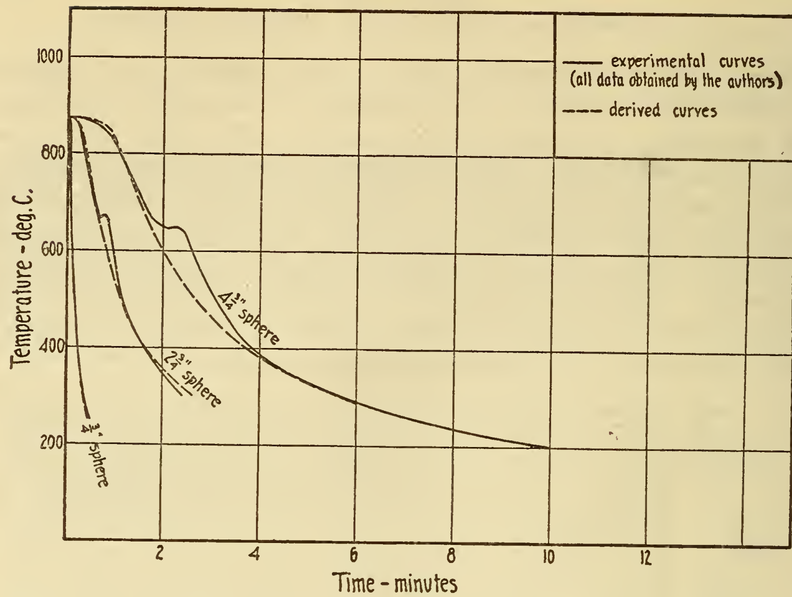


Fig. 8.—*Comparisons of derived and experimental oil-cooling curves for the center of various sizes and shapes*

Some of the properties of the oil used in these experiments (called No. 2 oil) are given in the publication referred to in footnote 2 of the text

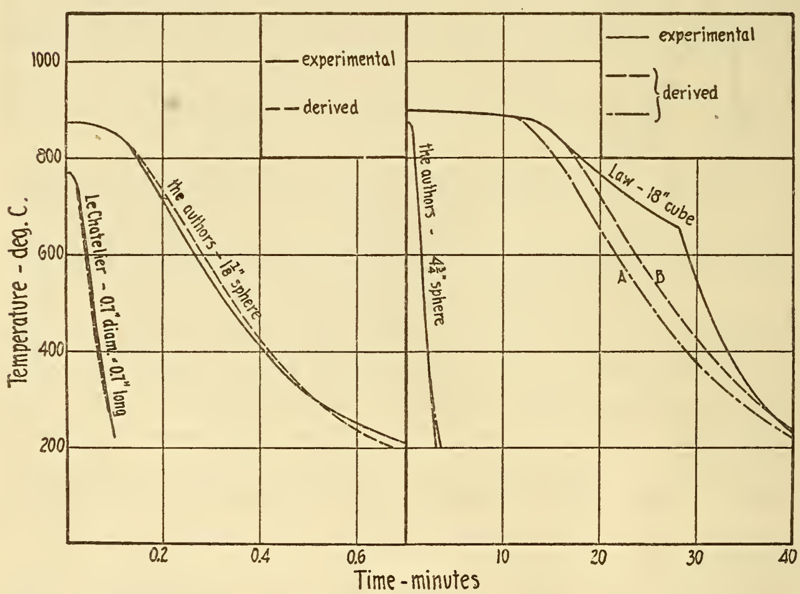


Fig. 9.—*Comparisons of derived and experimental water-cooling curves for the center of various sizes and shapes*

Le Chatelier's cooling curve obtained from Rev. Met. Mem., **65**, pt. 1, pp. 473–493; 1904

show that direct experimental confirmation is available for the described empirical relations covering a wide range in conditions. Naturally the derived values do not closely check all published results for like quenching conditions, but agreement is obtained with representative experimental data other than that obtained by the authors.

It will be observed in Figures 7, 8, and 9 that there may be appreciable variations between the derived and experimental cooling curves in the zones of thermal effects of transformations. There is no reason why these thermal effects should not be taken into account in determining the time-constants for a given coolant so that a closer approximation will be obtained throughout the entire cooling range, particularly for large masses. This was not done by the authors because the magnitude and position of the transformations vary with different steels, and as already stated in this report there were variations in composition of the steels from which the large and small specimens were prepared. The important feature to be emphasized is the similarity in a given coolant between the center cooling for various sizes and shapes which enables a resolution of cooling curves into two major components both related to the surface per unit of volume of the sample (1) an initial period called "lag" which represents 2 per cent of the cooling range and (2) thereafter the typical time-temperature changes characteristic of the particular coolant.

Attention should be called to Law's water-cooling curve for an 18-inch cube in Figure 9. The derived cooling curve for such a cube, based on the average "lag" from Figure 3, is shown by the dotted line *A* in Figure 9, which is generally parallel to but offset from the experimental curve given by Law. In other words, the major difference between the two is due entirely to the initial period or how soon after immersion in the water an appreciable center cooling begins. Comparison of Law's water-cooling and oil-cooling curves for the same cube shows the "lag" to be greater in water than in the less "drastic" oil quench. There is considerable evidence from various sources that this is improbable or at least associated with some unusual or not fully defined conditions in his experiments. If the actual "lag" scaled from Law's curve is used in place of the average lag for this size of cube given in Figure 3, the dotted line *B* in Figure 9 is obtained and closely agrees with the experimental values.

It should, perhaps, be pointed out that for large masses small differences in the surface per unit of volume result in relatively large changes in the "lag" due to the fact that the relation between these two factors is such that when plotted to logarithmic coordinates a straight line is obtained as in Figure 3. In other words, a supersensitive set of conditions are encountered, and unless these are

accurately defined when experimenting with large masses appreciable variations are to be expected in duplicate cooling curves, which may be generally parallel to but offset at some distance from each other.

Special attention should be called to the fact that the values of the exponent "$n$" of equation (5) are the same as, and apply equally well to, the relations between mass and cooling velocity previously described [9] as to the time-temperature relations dealt with in this report. This adds material weight to the validity of the described relations.

Another feature of interest lies in the relation between this coolant constant, $n$, and the "lag." Were it not for the fact that it is impracticable at this time to attain the desired degree of accuracy in the experimental work, the value of "$n$" for a coolant might be determined directly from Figure 4 after measuring the lag in the manner described when cooling some one size of the simple shapes in that coolant.

Aside from the determination of cooling times in typical coolants, the methods outlined make possible a correlation of data irrespective of size (of the simple shapes) and quenching temperature (when at or above about 720° C.) which heretofore has been exceedingly difficult if not impracticable.

There follows a summary of the main features of the described experiments.

1. In a given coolant the center of a sample of given size and shape cools in equal times to equal proportions of the cooling range. Thus, if temperatures are expressed as a proportion of the interval between the quenching and coolant temperatures, results obtained are directly applicable to any quenching temperature (when above the transformations).

2. When quenching various sizes of the simple shapes into a given coolant, the center cooling time minus a factor called "lag," is inversely proportional to the surface per unit of volume raised to some power greater than 1 and less than 2. If $T$=cooling time, $S$=surface area, $W$=volume, $n$=a constant, depending upon the coolant, $y$=the "time-constant" which, for a given coolant depends only on the cooling interval considered, expressed as a proportion of the cooling range, and $x$="lag," which is the time required for the center to fall 2 per cent of the cooling range, then these relations may be represented by the equation

$$T-x=y\left(\frac{W}{S}\right)^n \qquad (5)$$

[9] See footnote 1, p. 365.

3. "Lag," which refers to the time required for the temperature at the center to drop 2 per cent of the cooling range, increases with the size of sample and hence with decrease in the surface per unit of volume. It is greater for a given size and shape of sample in slow coolants such as air than in oil, and likewise greater in oil than in the more "drastic" water quench. While an equation can be derived giving "lag" in terms of the coolant exponent $n$ and the surface per unit of volume this has not been included in this report; instead a "lag chart" (fig. 4) was prepared from which values may be scaled directly for various sizes and shapes quenched into various coolants, provided only the coolant-constant $n$ is known.

4. From this chart and equation (5), above, time-temperature cooling curves may be derived for the center of various sizes and shapes quenched from various temperatures into ordinary coolants, provided only the coolant constant is known and there is available a cooling curve on some one size quenched into this coolant from some one temperature. It is, however, generally safer to base such calculations on determinations from several sizes if reasonably good accuracy is to be obtained.

## V. ACKNOWLEDGMENTS

Acknowledgment is made to T. E. Hamill, laboratory assistant, for his assistance in carrying out the experimental work, and to J. Fletcher Harper, of the Allis-Chalmers Manufacturing Co., Milwaukee, Wis., for supplying prior to publication the cooling curves on the 12-inch cube.

WASHINGTON, December 4, 1925.